Knowledge Inquiry in the Construction Management Domain through Structured Research Process and Methodology

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ABSTRACT

Construction works are project-based and interdisciplinary. Many construction management (CM) problems are ill defined. The knowledge required to address such problems is not readily available and mostly tacit in nature. Moreover, the researchers, especially the students in the higher education, often face difficulty in defining the research problem, adopting an appropriate research process and methodology for designing and validating their research. This paper describes a 'Horseshoe' research process approach and its application to address a research problem of extracting construction-relevant information from a building information model (BIM). It describes the different steps of the process for understanding a problem, formulating appropriate research question/s, defining different research tasks, including a methodology for developing, implementing and validating the research. It is argued that a structure research approach and the use of mixed research methods would provide a sound basis for research design and validation in order to make contribution to existing knowledge.

Keywords: BIM, construction knowledge, research design, research question, validation

INTRODUCTION

Research in construction engineering and management (CEM) is rapidly growing. It applies different research methods and approaches developed in the domains such as, manufacturing, social sciences, computer science, and information technology. Due to the inherent nature of the construction industry, there are methodological challenges to conduct practically-relevant and scientifically sound research (Taylor et al. 2011; Fischer, 2006). Designing and developing a research platform is a "blueprint," a logical plan, more than a work plan, for getting from here to there, i.e., from setting up the research question to answering the research question through the logical model of proof (Yin, 2009). It is an iterative process, the process that is refined as the researcher gains more knowledge about the research problem and the methodology to be adopted through a better understanding of the problem. Proper research planning and design and sound methods can aid to this process and increase the validity, reliability and generalizability of a research study.

The research presented in this paper is guided by the 'Horseshoe' research process (Fischer, 2006), an iterative process that is driven by the observation of the practical problem, a thorough literature review and case studies, to name a few. An important aspect of it is the use of triangulation that uses multiple techniques to formalize the construction knowledge, implement prototypes, and ultimately, validate the developed research. The use of multiple methods in a research study requires little explanation, as different research methods overlap in many ways because they are not marked by sharp boundaries (Yin, 2009). Mixed research methods can also help to minimize bias, generalize the results and to improve the credibility of the research results.

The purpose of this paper is to describe the major steps of the 'Horseshoe' research process and its application to address a research problem of extracting construction-relevant information from a building information model (BIM). The implication is that CEM research community could benefit by leveraging a structured research framework and multiple methods in the design, implementation and validation of practically relevant and theoretically sound research studies.

CONCEPTUAL RESEARCH PROCESS FRAMEWORK

This research used "Horseshoe" research process framework (Figure 1). This framework was developed at the Centre for Integrated Facility Engineering (CIFE) at Stanford University (Fischer, 2006). It provides a conceptual framework for construction researchers to design and validate the real-world research problems. "*This method supports researchers in building on the experiential knowledge and anecdotal evidence that can be gathered on construction sites in the context of existing theory and expert knowledge to carry out practically-relevant and scientifically-sound research*" (Fischer, 2006). In the following sections, we describe the important concepts of this framework and how it was applied to the research problem of enriching BIM with construction-focused information and retrieving useful and relevant information from the product-centric BIM using queries.

Observed problem in practice

The practical motivation for the research presented in this paper emerged from the observation of current work practice related to the use of BIM for construction. It was found that many of the design conditions that matter to construction practitioners were not explicitly represented in current BIMs. The visual inspection and manual analysis of BIM to identify this kind of design information can be unreasonably difficult, especially for large and complex projects. Current approaches to automatically extract construction-specific design information also found inadequate to fulfill the unique requirements of construction and other downstream processes.

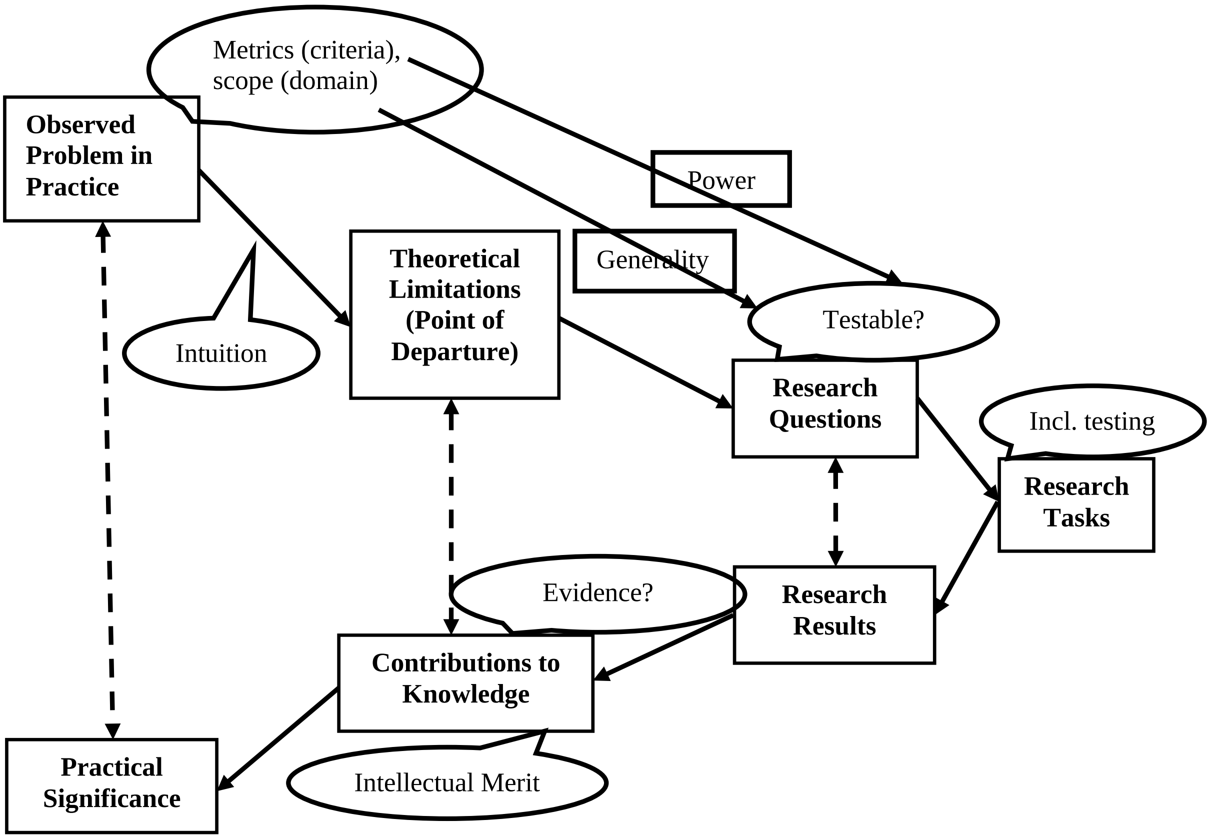

Figure 1 CIFE ‘Horseshoe’ Research Process (Adapted from Fischer, 2006)

Intuition

An intuition relates to how the observed problem could be addressed generically, or independent to a particular construction project (Fischer, 2006). Our intuition was that an ontology of design conditions could formally, generically and flexibly be developed using the manufacturing concept of “features” (Cunningham and Dixon, 1988; Shah, 1991), and that formal mappings could be created using XQuery (W3C, 2010) to map each concept defined in the ontology to a corresponding design concept in the standard schema, such as ifcXML representation of BIM data, in order to automatically extract features. The second intuition was that a query vocabulary combined with reusable, customizable and computer interpretable query templates might yield an effective solution that would help non-expert BIM users to easily and quickly formulate spatial and non-spatial queries on BIM to extract specific, relevant and useful construction information out of it.

Points of departure

A thorough review of a broad spectrum of literature was conducted to further enhance the understanding of the research problem, identify the existing work that is useful in addressing the problem, and identify the techniques that could be used to address the problem. This research builds on, combines, and extends previous research on design relevant construction knowledge, ontological modeling, feature-based modeling, building product models (or BIMs), and product model reasoning. The review also focused on state-of-the-art BIM analysis tools such as *Solibri Model Checker*, *Autodesk Navisworks*, and *Innovaya*. This broad spectrum of literature and analysis helped the researcher to identify the research gap and provided a basis to formalize the feature ontology and query specifications (to be discussed later).

Research questions

Research questions were developed based on the identified problem and the research gap, and through thoughtful and extensive literature review. Three research questions, as described below, were investigated.

<u>Research Question 1</u>: *How can construction-specific design conditions be formalized to support extraction and querying of a building information model (BIM)?*

Different types of spatial and non-spatial design conditions, such as component intersection, location, size, shape, layout, type, spacing, uniformity/similarity impact construction. Construction practitioners scrutinize these design conditions (and others) in every building project as they are critical to a variety of CM functions, including constructability assessment, productivity analysis, method selection, and cost estimating. Ontologies, which are explicit specifications of a conceptualization, are highly useful for representing domain specific knowledge (Gruber, 1995), such as knowledge about construction-specific design conditions. The feature ontology generically defines design conditions using the manufacturing concept of ‘features’ (Shah, 1991) and acts as a semantic layer between the end users and the BIM. The feature ontology extends the underlying representation of BIMs by explicitly representing construction relevant concepts related to components (e.g., walls and columns) and intersections (e.g., penetrations and openings) as features. It enables automated feature extraction from a BIM and provides support for answering user queries.

<u>Research Question 2</u>: *How can query specifications be formalized to support spatial and non-spatial queries on BIMs?*

Construction practitioners look for different design conditions in a given design to account for them properly in support of various CM tasks, such as cost estimating, methods selection, constructability analysis, and construction planning and execution. Practitioners have varied preferences for what design conditions are important, when they are relevant and how they impact construction. There is limited understanding about how to represent and characterize them to facilitate user queries. There is also a lack of computer support to enable users to easily and flexibly define queries from a BIM. This research question addresses this issue by developing formal query specifications and templates. It identifies different types of queries and their attributes that are relevant to practitioners when analyzing a BIM. The attributes can be customized and specified by the user during the query formulation process.

Research Question 3: *How can an integrated approach leverage the representations formalized in (1) and (2) to enable automated processing of user-driven and customizable queries on BIMs?*

The third research question formalized an integrated approach that combines the research questions 1 and 2 for answering user queries on BIMs. The approach integrates the generic feature ontology and project-specific FBM with the query specifications. The prototype application, the '*Feature Extractor,'* automatically extracts the features in a given BIM based on the feature ontology to create a project-specific Feature-Based Model (FBM). The resulting FBM enables practitioners to browse and navigate the features in a given design, thereby providing an increased understanding of the features present that may impact construction. The FBM also forms the knowledge base for answering users' queries about a given design. Another prototype application, the '*Feature Query Analyzer'*, provides support to answer user queries on the FBM. This application processes queries based on the query vocabulary and in accordance with the query specifications specified by the user.

Research tasks

Developing this research involved several tasks. The distinct tasks carried out include: (i) knowledge acquisition, (ii) development of the research framework and related components, (iii) prototype implementation, and (iv) evaluation/validation studies. These tasks are summarized below:

Knowledge acquisition

Knowledge from different sources was acquired to formalize the feature ontology and query specifications (Nepal, 2011). The major undertakings include: extensive literature review, case studies, observation of design and construction meetings, observation of the actual work practice of construction practitioners for analyzing a design, and discussions and interactions with practitioners. These undertakings also helped the researcher to develop motivating cases and identify research requirements.

Development of the research framework and related components

A general research framework (Figure 2) for extracting information and querying a BIM was developed using an IDEF0 (Integrated Definition for Function Modeling) technique (Colquhoun et al., 1993). The specific components of this framework include the development of: (a) the feature ontology, and (b) query specifications and templates. Basically, the feature ontology and query specifications that explicitly represent or describe domain concepts related to design conditions important from the construction perspective, represent symbolic domain models (or formalizations). These domain models are used to access and manipulate BIM data and analyze a BIM, a virtual representations of real world buildings.

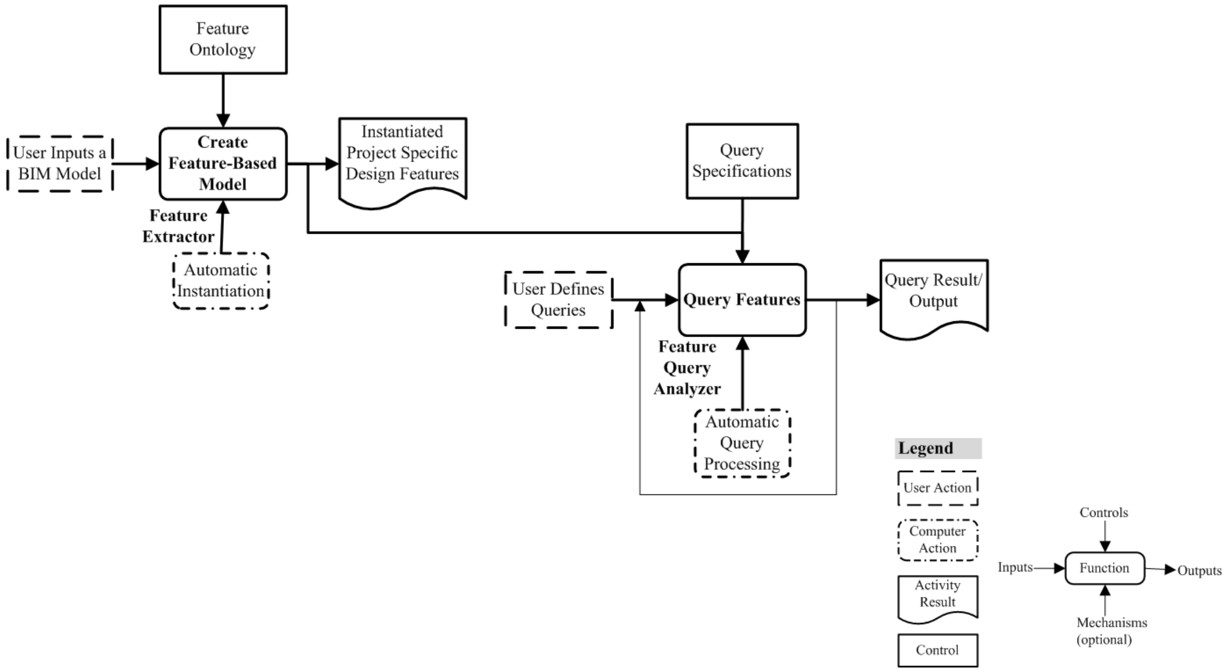

Figure 2 A Framework for Extracting Information from a BIM (Adapted from Nepal, 2011)

In the first step (**Create Feature-based Model**), the prototype application, '*Feature Extractor*' transforms the input *IFC*-based BIM into a project-specific feature-based model (FBM) that explicitly represents the features that are important to a particular construction practitioner or domain. For this step, we formalized a *feature ontology* to generically represent construction-specific design conditions. In the second step (**Query Features**), users configure queries that operate on the project-specific feature-based model. The system takes the query input from the user and executes the application '*Feature Query Analyzer*' to process user queries. For this step, we developed *query specifications* to formalize the language and structure of the user-driven queries in relation to a BIM. The query specifications define a query vocabulary and attributes to specify different types of spatial and non-spatial queries.

Prototype implementation

The feature ontology was formally represented in *Protégé Frame Editor*, an open-source, ontology development platform. The *Protégé-Frame Editor* provides a suite of tools for building domain models and knowledge-based applications with ontologies (*Protégé*, 2008). The author worked with computer science researchers at the University of British Columbia to develop two prototype systems: (a) the '*Feature Extractor'* to automate the extraction of features in order to create an FBM, and (b) the '*Feature Query Analyzer'* to automatically process queries according to the taxonomy of queries and query specification definitions. The input data to the system comes from a 3D BIM model modeled in an IFC-compliant 3D BIM application (in our case, a Revit). The XML representation of BIM data is used for feature extraction and answering queries. We used the standard XML query language, XQuery (W3C, 2010), to extract and query features. More detailed description of the feature extraction process is described in Nepal et al. (2013). Nepal et al. (2012) describe the process and mechanism for querying spatial construction information from a BIM model.

Validation

Three different tests were carried out to validate the research. A number of metrics (or criteria), mostly subjective in nature, were used to gather evidence for the power and generality of the research, including the content and soundness, and intellectual merits. A brief discussion of the tests performed is provided below. A detailed description of the validation studies conducted is provided in Nepal (2011).

Detailed interviews

We conducted interviews with four construction experts to validate the 'content' and 'representativeness' of the concepts formalized in the feature ontology and query specifications. The interviews provide the wisdom of authorities gained from the experts' experience and work (Neuman, 2006). Personal interviews with domain experts are the most valuable and effective way to acquire domain vocabulary or knowledge and receive immediate data and feedback to verify the implemented system (Carrico et al., 1989). The evidence gathered from interviews also shows the 'generality' of the knowledge formalized in this research as four different experts representing different construction domains and viewpoints provided their inputs on the design conditions that matter to them, reasons behind why they matter, and the conditions under which they would be relevant.

Retrospective analysis

We developed 'retrospective analysis' based on interviews, case studies of four different projects, and a thorough literature review to demonstrate the 'soundness' of the research approach in relation to the state-of-the-art tools. We designed retrospective analysis of design conditions related to a “component” in general, “wall” and “column” components in particular, and “component intersection,” “opening,” and “penetration” features. This test also demonstrates the ‘generality’ of the approach as this research enables practitioners to extract or query different deign conditions for different components, component intersections, openings and penetrations features.

Descriptive and interpretive analysis

Finally, we performed ‘descriptive and interpretative analysis’ of the developed research to demonstrate its “intellectual merits.” The technique employed is largely what social scientists refer to as “second-order interpretation.” In the context of this research, the “second-order interpretation” is qualitative interpretations from the point of view of the researcher who conducted the study (Neuman, 2006). As such, the analysis provided empirical interpretation and evidence to demonstrate the significance and validity of the developed research.

Research results

The research results need to answer the research questions (Fischer, 2006). For the research discussed in this paper, the results include: (i) the feature ontology that generically represents design features relevant to construction, (b) the feature-based model that represents project specific features and the FBM browser, (c) the specification of the queries and query templates and the implementation of queries, (d) the integrated framework and its implementation to automatically extract features and answer queries to identify the required information from a BIM, (e) insights from the validation tests, particularly from interviews with domain experts and also through the descriptive and interpretative analysis.

Contribution to knowledge

The hallmark of any good research lies in its novelty and unique contribution to knowledge. The knowledge created is expected to extend the previous work and address gaps in research, enhance the existing knowledge in a given domain or discipline, and provide a sound basis for further research. The main contributions to knowledge resulting from the research reported in this paper can be summarized as: (a) the formalization of an ontology of design conditions; (b) the formalization of a query specification vocabulary, and the development of query templates to specify spatial and non-spatial queries on features; and (c) the formalization of an integrated approach to automatically instantiate features of a feature ontology for a particular BIM model, and to answer user-driven and customizable queries.

Practical significance

The nature of research in the built environment generally falls either to a basic research or applied research type. In contrast to "basic research," where the inquiry is to better understand or explain the phenomena, "applied research" is directed at end users and seeks to provide practical solutions to concrete problems, or addresses the specific needs of the end users (Neuman, 2006). Most applied research is however first thought in terms of its practical significance to solve real world problems and worked backwards to design an appropriate research methodology (Fischer, 2006). The practical significance of the research highlighted in this paper lies in automatically extracting construction-specific design information from a BIM model and answering user queries about features of a design, with an overarching goal of improving efficiency and effectiveness in decision making process in construction. A sound research method or approach is also characterized by the generalizability of the approach to be able to apply it to solve similar problems in a given discipline or across the related disciplines. While this research is primarily driven from the construction perspective and targeted to construction practitioners, the approach can be employed to the design phase for designers to support design analysis and to facility management phase for making facility management decisions.

CONCLUSION

Given the interdisciplinary nature of the research and the increasing use of BIM in building and construction industry, there has been and will be an increasing demand for application of rigorous and objective research methods. Researchers need to incorporate multiple (or mixed) methods for knowledge acquisition and formalization, rigorous data collection and analysis, prototype implementation, and research validation. However, in order to utilize a mixed method approach, one would need sound methodological principles at each stage of the research (Abowitz and Toole, 2010). The research presented in this paper used the "Horseshoe" research process as the overall framework for systematic knowledge inquiry. It employed multiple methods (e.g., observational studies, case studies, state-of-the art reviews of BIM technologies, interviews with and insights from domain experts) to research design, implementation and validation.

The research that involves formalizing knowledge and leveraging BIM for construction and facility management is very challenging. Firstly, it is very hard to measure the benefits and improvements of new approach over the conventional work practice/s in terms of discrete quantitative terms, as there are no agreed upon standards or metrics for evaluation. Secondly, exact replication of any sort of tests or experiment in a real world situation or on projects of sizable scope and complexity is often very difficult to achieve. Moreover, most research involving IT applications in construction doesn't exactly fit to the continuum of qualitative and quantitative research techniques.

Construction works are project-based, temporary and interdisciplinary in nature, with complex networks of project organizations and stakeholders. There are inherent challenges in conducting scientific studies or inquiry in construction and ensuring the validity and reliability of a research study (Lucko and Rojas, 2010). As such, no single research method or approach is ideal for research design and validation, as each method has its own strengths and limitations. The choice of using a certain research method and the burden to prove the validity of the approach largely depends on the type of research study undertaken and the problem or research question/s that it needs to address, among others. However combining different research methods (i.e. mixed research methods) such as in the form of triangulation, although it may require more resources and efforts, can improve the validity and reliability of a research study (Abowitz and Toole, 2010). Leicht et al. (2010), for example have shown that observational studies, (more extensively the ethnographic studies), that employ both qualitative and quantitative approaches have substantial advantages. They are useful not just for understanding the problem and phenomenon but also to generate quantitative information and provide the contextual information to more completely understand a given phenomenon (Leicht et al., 2010).

It should be mentioned that not all research would fall or fit exactly to the "Horseshoe" framework. A significant variation may exist in carrying out research tasks, defining proper metrics during the problem definition and subsequent validation stage, and using appropriate validation strategies, among others. The framework however provides a sound basis and guidance for researchers in conducting applied research in the domain of construction. A thorough application of the underlying concepts or elements and the overall process can help researchers to make significant contribution to knowledge by producing a good quality research that is very practical, defensible, and grounded on existing practice and theory.

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